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HANDBOOK FOR SEISMIC PERFORMANCE TESTING OF BRIDGE PIERS

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SUMMARY

In order to provide assistance to seismic performance investigators in efficiently producing or obtaining consistent and reliable experimental testing results, Federal Highway Administration developed the "Handbook for Seismic Performance Testing of Bridge Piers"(name subject to modification at publication), which contains information on preparation, execution, and documentation of such testing. This document is purported for use in both academic research and engineering validations. It provides elaborate description on an assembly of available testing procedures while alternatives are offered for special test needs. Although most existing testing procedures are for steel or concrete pier columns, restriction on material is not explicitly specified in this document. Elements with advanced material can be tested using the listed methods. Requirements on testing record are given, so to allow many users to access and verify the testing results in a later time.

Assistance from experienced experimental experts and bridge engineers were requested during the development of the document. An expert panel including members from academia, state highway agencies, and federal government, was assembled to advise the progress and review the product. At the time of completion of this paper, the FHWA guidance document is at its final stage of technical revision and will be published in a short time.

INTRODUCTION

Background

The performance-based bridge design approach has been gaining attention in recent years. In order to accurately estimate the life cycle performance of a structural element under various potential seismic hazard, a large amount of reliable and comparable results from seismic performance testing are in great demand. Testing results must be produced by the process and equipments that meet or exceed a preset

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quality requirement. The performance data must adequately describe the testing condition and observed phenomena, and be archived in a compatible format with other data.

There are currently a few guidance documents available for seismic performance testing. The Applied Technology Council (ATC) published a protocol for cyclic seismic testing of components of steel structures in 1992(ATC [1]). In 1997, the SAC program (a joint venture of SEAOC, ATC, and CUREe) published a testing protocol specifically developed for steel moment-frame building testing (SAC Joint Venture [2]). The ATC protocol and SAC protocol were developed for research purpose. The adoption of these protocols as acceptance criteria for steel building design by the "Seismic Provisions for Structural Steel Buildings" of the American Institute of Steel Construction (AISC) invested these protocols with proof-test protocol status. The American Concrete Institute (ACI) also adopted a similar acceptance testing protocol for concrete moment frames since 1999 (ACI [3]). The Consortium of Universities for Research in Earthquake Engineering (CUREE) woodframe program developed a series of loading protocols for cyclic testing of non-ductile elements under regular and near-fault earthquakes in 2001 (Krawinkler et al [4]).

The early effort for developing the guidance documents is more concentrated on seismic performance of steel moment-frame systems that represent a significant amount of public buildings. The procedures customized for such purpose are not always adequate for bridge piers. For example, the SAC loading protocol was developed using fixed values of drift rotation (by %) to designate the deformation level. This was found convenient and adequate for steel moment frame components and joints on buildings because of the limited variation of building element dimensions. This protocol may not always be adequate for bridge piers because of the large variety of aspect ratio and cross-sectional configuration.

Seismic load of the bridges imposes large dynamic force (comparable to gravity load) in horizontal and vertical directions. Due to the dynamic essence of the seismic load, many limit states, such as yielding, can occur multiple times within the duration of an earthquake and aftershocks. The recurrence of the limit states depends on the earthquake load history and sequence of aftershocks. Such path-dependency introduces a number of variables that diversifies the testing procedures. Many different procedures have been practiced for various subjects located in different seismic zones.

Existing difficulties

A significant investment of funding and labor on bridge testing does not guarantee effective assistance to design and construction. In this study, the following obstacles and shortcomings were found prevailing in current experimental research for seismic design and analysis of bridge structures:

(1) Test results from different organizations or researchers cannot be compared and synthesized due to a lack of generally agreed testing and loading conditions.

(2) The use of test data by other researchers or engineers may be handicapped by a lack of consistent documentation methods, minimum required information on test conditions, and measurements.

(3) Consensus-based test loading protocols for seismic performance evaluation of bridge piers do not exist.

The seismic performance database is an essential tool for performance-based bridge design. Existing databases, such as that maintained by Hose et al [5], consist of basic descriptions of the testing facility, identification of limit states, and the load-deformation relationship. Many of these data were produced with little consideration of being used in performance database. Very limited information was provided by such testing. The database in the future will contain much more measurement and information to allow the development of more versatile and reliable performance-based design criteria. A guidance document that lays out the minimum requirements for the seismic performance testing can much reduce the difficulty in the development of the performance database.

Development of FHWA guidance document

Seismic performance testing of bridge piers is an expensive but highly rewarding commitment for the transportation authority. The quality and efficiency of pier testing greatly impacts the public welfare for its significance in public safety and budgetary control. Such attribute makes the research for pier testing methodology a national-level interest. In order to assist researchers and engineers in this country to obtain reliable seismic performance testing data of bridge piers, the Federal Highway Administration (FHWA) conducted a study on the methodologies and current practice of seismic performance testing of bridge piers to identify adequate practice. A guidance document is produced as a result of this study.

The guidance document provides minimum requirements in specimen preparation, loading program, and instrumentation/documentation. It also clarifies and synchronizes the engineering language used in experiments and engineering practice. The targeted users include experimental and theoretical investigators as well as bridge engineers. The guidance document is not an entry-level tutorial that allows any inexperienced person to sample pieces of testing procedures, slap together, and produce an experimental project. Each testing project can carry unique requirements or difficulties that need engineering and experimental expertise to cope with.

The FHWA testing guidance document is developed specifically for bridge pier testing. Because many testing facility have become capable of performing dynamic and hybrid testing, guidance to such testing (based on current knowledge) is provided. Material restriction is minimized to accommodate various types of bridge pier material including steel, concrete, wood, and composite material.

RATIONALE OF BRIDGE PIER TESTING

Before committing any experimental activity, one must consider thoroughly the rationale of using the experimental approach. The adequate procedure can then be selected based on the objective of the study, available funding, and capability of the testing facility.

Functions of testing

A seismic engineering problem can be resolved by a series of analytical (derivation and computation) and experimental studies. Experimental studies are needed when

1-a There is a lack of knowledge to define the problems and to initiate analytical studies regarding an engineering subject (e.g. structures or structural components) or a type of seismic hazard.

1-b Relationship among identified parameters, that is, an analytical/empirical model, needs to be established.

2 Applicability of established analytical models or design criteria to specific engineering practice needs to be verified.

Stages 1-a and 1-b carry the functions of a theoretical research while stage 2 carries the function of proof-of-concept study. Stages 1-b and 2 are similar to the system characterization test and prototype test stages, respectively, described in AASHTO seismic isolation guide specification (AASHTO [6]). It is, however, a common understanding in the bridge engineering research community that a test can and should serve multiple purposes. For example, a proof-of-concept cyclic loading test is considered completed when all the desired performance levels are achieved, i.e. requirements on displacement amplitude and number of cycles are satisfied. Many specimens may not have failed at this point. The testing can go on using protocol-recommended or custom-determined amplitude increment and number of cycles until imminent collapse. The part of the testing beyond the proof-of-concept scope can have significant academic value in revealing important mechanical property of the subject for further study.

Types of Testing

The guidance document developed by FHWA uses loading process to distinguish types of testing in the document. The loading can be either a prescribed program or a result from the dynamic response of the specimen. The location of the loading can be distributed or concentrated. The speed of the loading can be slow (quasi-static) or fast (dynamic). The matrix shown in table 1 presents the relationship of these criteria and the common names of the testing types they are associated with.

Table 1 Types of testing distinguished by loading programs

Loading / Speed	Prescribed displacement loading	Inertia loading (or non-prescribed displacement loading)	
		Distributed load	Point load
Slow	**(A)** Quasi-static Monotonic loading (A1), Quasi-static cyclic loading (A2)	N/A	**(D)** Pseudodynamic tests
Fast	**(B)** Fast monotonic loading (B1), fast cyclic loading (B2).	**(C)** Distributed mass shaking table tests	**(E)** Lumped-mass shaking table tests (E1), effective force tests (E2), hybrid tests (E3)

The selection of loading methods affects the testing in many aspects. In addition to the different requirements on load application apparatus, the specimen design and measurement system may have unique requirements for each option in table 1. The fast testing is normally advantageous in obtaining realistic response for specific bridge and event, while the slow testing often provides general response for a group of bridges in a certain range of area. The pseudodynamic testing is carried out in low speed but theoretically provides dynamic response of the subject bridge in a specific event. In low speed, it is easier to make necessary modification during the test to accommodate unexpected situations. With the same specimen size, the slow testing cost less and have lower demand on facility space, structural strength and rigidity, and hydraulic power capacity. It is therefore very common to select slow testing when a large-scale specimen is required.

The prescribed displacement loading programs provide general representation of seismic performance while and inertia loading programs provide very specific performance information for a given event. The prescribed displacement (cyclic, monotonic, etc.) does not resemble any real earthquake response. The programs are designed to allow the specimen to exhibit multiple limit states and obtain abundant mechanical property in one or very few tests. The ductility and damage level are very easy to compare with those of other tests because of the consistent displacement history. The inertia loading produces the similar force as that in a real event. Each specimen can fully demonstrate its unique dynamic behavior in a certain event. The results, however, depend on the selection of the loading time history.

The concentrated load condition is an assumption that is very convenient for most seismic performance testing of bridge piers. This assumption is based on the fact that the most significant mass is concentrated in the superstructure. In addition, the force from the superstructure produces the most severe combination of flexural, axial, and shear stress at the lower part of the pier (sometimes also on upper part—for double-curvature configurations). It is difficult, although achievable, to apply distributed load by loading apparatus. The easier way to conduct distributed load testing is to use inertia force produced by the mass of the structural body excited by a shaking table (type C testing). Such testing can precisely reproduces the real structural behavior. The utilization of structural mass imposes more restrictions on scaling and possibly increases the cost and equipment requirement.

Type B testing is a simplified approach to include stress/strain rate effect. Unfortunately, it suffers a necessary distortion in the similitude when scale model is used. In case of necessary type B testing for specific project, full-scale specimen is preferred.

Procedures of testing

A typical experimental testing project of bridge piers contains three components: specimen preparation, loading program, and measurement/documentation. Figure 1 shows the chronological relationship of these components. In the FHWA guidance document, various options for each component are collected and explained. The user can choose proper options that are suitable for the testing objectives and limitations. Different testing options contain different assumptions and offer valid results under these assumptions. The equipment requirements and cost of the different options also vary. The chosen testing method should be able to provide desired testing conditions while keeping the equipment and budget requirements within reasonable range. It requires much engineering knowledge and professional experience to make sound selection and modification on existing testing procedures as well as producing innovative testing procedures.

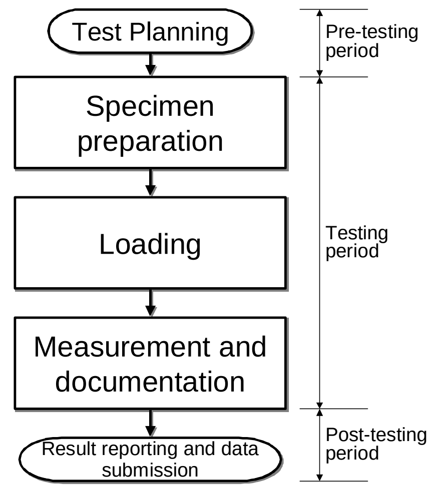


Figure 1 Components of an experimental project

SIGNIFICANTISSUES IN EXPERIMENTAL PROCEDURES

Similitude

Full scale testing can best reflect the behavior of a bridge pier in working condition. However, it can be very expensive or even impossible for most testing facilities. Scale model can well represent the real pier to a certain extent if the similitude laws are followed adequately.

Due to the difficulty in changing material property, the perfect compliance for all parameters to the straightforward similitude law is neither practical nor required all the time. Proper assumptions can be used based on engineering knowledge and experience. For example, the majority of the mass for many bridges is concentrated in the superstructure. For scale model of these bridges, the inconsistency with similitude law for density scale factor is tolerable. Only the total mass of the superstructure needs to comply with the similitude requirement. This simplification is based on the knowledge that the only contribution of density to the specimen behavior is the mass of the pier and this mass is negligible in the seismic loading mechanism for such piers.

The requirement of compliance to similitude law can be different for tests that carry different functions. In general, the theoretical researches tend to focus on effects of specific structural parameters and therefore do not always require strict similitude. Smaller scale model can more often be used in theoretical researches. Proof-of-concept testing bears the duty of validation for implementation.

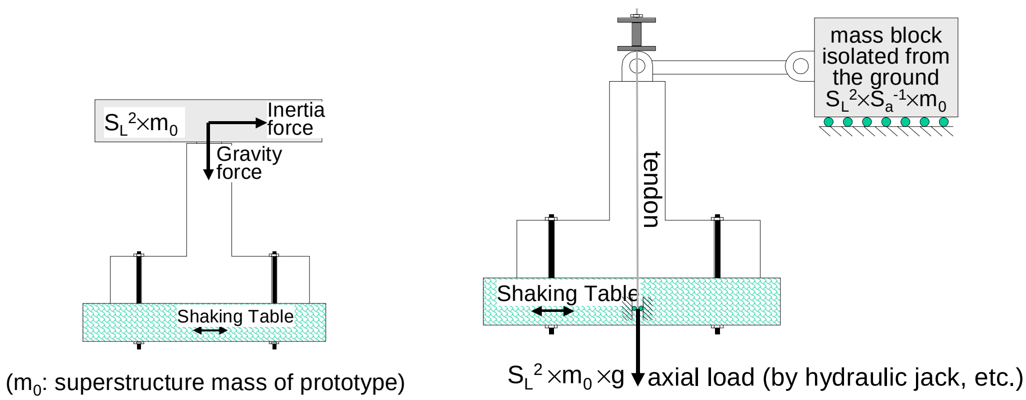
The most common scale factors used in seismic performance testing are listed in table 2. All scale factors are represented by the linear size, S_L (less than one for reduced scale). Material properties are kept unchanged for the ease of specimen fabrication. The assumption tagged along this scaling system is that

(1) the mass in the pier is insignificant, (2) the rate-dependent stress is insignificant, and (3) there is no flexibility in superstructure. It is most appropriate to type E testing.

Table 2 Typical scale factors

Variable	Scale factor
Length	S_L
Time t	$S_L^{0.5}$
Stress σ	1
Strain ε	1
Elastic modulus E	1
Force P	S_L^2
Displacement U	S_L
Bending moment M	S_L^3
Curvature φ	S_L^{-1}
Acceleration	1
Superstructure mass (weight)	S_L^2
Frequency	$S_L^{-0.5}$

There are many variations for this scaling system. Each variation contains additional assumptions based on the requirements of the testing. For example, figure 2(a) is a typical type E1 test setup that uses the scale factors listed in table 2. The setup in figure 2(b) separates the axial loading mechanism from the lateral loading mechanism. The tie between the gravitational acceleration and the horizontal earthquake ground acceleration is removed. An additional scale factor for lateral acceleration, S_a, is produced. This additional freedom is useful to accommodate the limitation of the facility. If the shaking table has insufficient displacement capacity, a lower amplitude (S_a<1) can be used for ground motion while a larger mass block ($S_L^2 \times S_a^{-1} \times m_0 > S_L^2 \times m_0$) is employed to produce the adequate lateral load.



(a) (b)

Figure 2 Mass scaling (a) typical (b) alternative for free acceleration scaling

Size effect of material

The size of structural elements can affect the mechanical properties of the construction material. There has not been a commonly accepted conclusion on the significance of the size effect and how it can be controlled in seismic performance testing. Current consensus is to

(1) Make large scale testing when possible. Full-scale specimen is especially preferred for proof-of-concept testing.
(2) Use original construction material cautiously. Make necessary modifications based on professional judgment (reduce aggregate size, use different grade steel, etc.).
(3) Conduct rigorous material testing and maintain complete record.

Limit states

Limit states are the vocabulary that the engineers use to communicate in seismic design. It is important to synchronize the definition of each limit state used in experimental testing and in engineering practice so that the testing results can provide answers to engineering problems accurately.

The bridge design guides normally specify global limit states such as “minimal to none damage” or “significant damage” (NCHRP 12-49 report, by MCEER [7]). The limit states observed in most pier testing, on the other hand, are local phenomena that involve only one structural member (i.e. pier column) or a part of the member (e.g. steel yielding, concrete crushing). These local limit states in the pier can be roughly associated with the global limit state of the bridge structural system. In this study, the limit states set forth in the NCHRP 12-49 report (MCEER [7]) for bridges, FEMA-368 for building construction, FEMA-356 for existing building assessment, and a study that correlates different descriptions for limit states (Hose et al [8]) are compared and approximately associated in table 3. This relationship is especially useful for bridge piers because the integrity of bridge piers directly controls the safety and functionality of a bridge.

Table 3 Local limit states and associated performance level

Experimental Limit State	NCHRP 12-49* Sevice Level	NCHRP 12-49* Damage Level	FEMA 369 (2000) Performance Level	Hose et al (2000) Performance/damage
Onset Cracking	Immediate	None	Operational	I
First Yield		Minimal	Immediate Occupancy	II
Element Yielding (Plastic Hinging) Ultimate Strength Spalling	Significant Disruption	Significant	Life Safe	III
			Near Collapse	IV
Failure	Not permissible	Not permissible	Not permissible	V

One of the most important limit states directly used in bridge design is the yielding of the element. The “ductility” commonly used in describing the performance of a structural member or system is defined with the yielding deformation. The yielding of bridge piers is seldom an abrupt event. Difficulty in determining yielding displacement has been a constant irritation to the designation of loading programs. When a different method to determine the yielding event is used, the same loading program can produce very different testing conclusions.

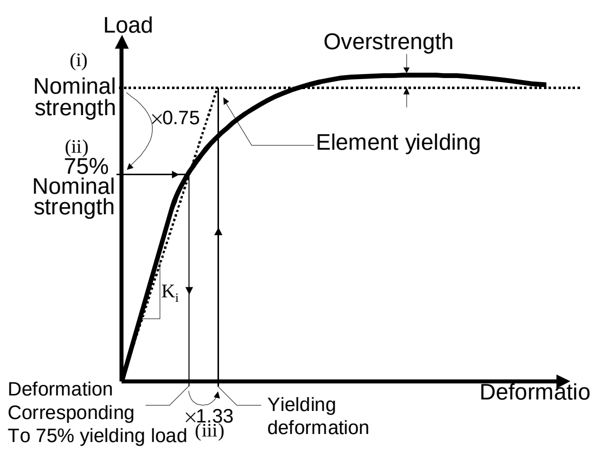


Figure 3 A sensible yielding definition

Figure 3 shows the definition of element yielding recommended in ATC-24 for use in designating the amplitude of cyclic loading program. It is not necessarily the best definition available, but is sensible and easy to use. It assumes the intersection of the load-displacement curve and its bilinear idealization to be at 75% of the nominal strength.

Definitions of other limit states such as cracking, first yield (not to be confused with element yielding), ultimate strength (overstrength included), and failure are reasonably consistent and can be found in the FHWA guidance document.

Loading program

The loading method is the primary factor to distinguish different types of testing procedures in the FHWA guidance document. The advantage of the inertia load options (types C, D, and E) is the capability of reproducing structural response in a specific seismic event. The selection on the loading program is relatively straightforward and based on user demand. The prescribed displacement options, on the other hand, aim at providing maximum amount of information on mechanical properties and limit states of the pier for general seismic event. More consensus-based criteria are needed for such purpose. While it is desirable to have fewer variations (easy to compare), it is very difficult to compose one displacement loading program that fit all research needs. The FHWA guidance document collects the most widely accepted loading programs that are suitable for bridge pier testing.

(1) Monotonic loading

This is the most essential program for seismic performance testing. It not only provides fundamental mechanical properties of the specimen but also supplies useful information for development of more sophisticated future testing. As an advantage for testing new technology or unfamiliar phenomenon, such program is relatively safe and allows much interference from the researcher. Two important factors need to be considered in developing the program:

(a) Maintaining sufficient margin of force and displacement capacity to ensure the observation of all desired damage level.
(b) Selecting reasonable loading speed and data sampling rate to obtain adequate amount of data and observations.

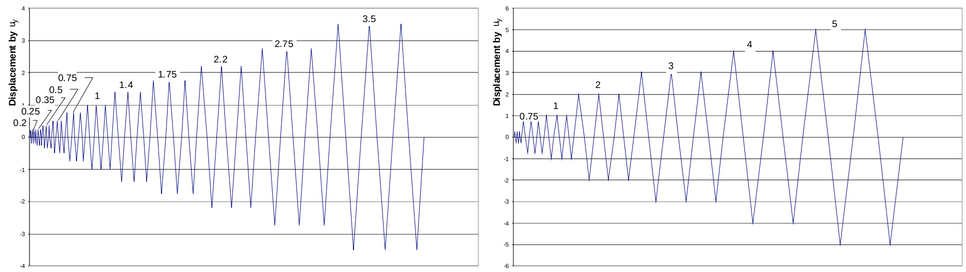
(2) Cyclic loading

The cyclic loading is one of the most versatile programs. The general earthquake response is simplified to a format with only three variables: amplitude, number of cycles, and sequence. The choice of each variable determines the properties of the earthquake the program simulates. If the chosen increment of the amplitude is too large, the test will finish in a shorter time and the recurrences of some limit states may not be well examined. Opposite situations occurs when a smaller increment is chosen. At the same displacement level, smaller increment produces more severe damage because of larger number of total cycles sustained below a certain amplitude level. Low-cycle fatigue can occur at low amplitude if small increment is selected. A large number of cycles at each load level results in more severe deterioration and softening than realistic earthquake loading, consequently leads to a lower lateral load resistance. The number of cycles with large amplitude should have less repetition because structures normally experience only a few large cycles in an earthquake. If the increment is selected to be large, the program represents short duration, high-amplitude earthquake. If the increment is selected to be small, the program represents earthquakes that shake in an intermediate level for a long time. The existing cyclic loading protocols are developed based on statistic studies on earthquake responses and the considerations of obtaining maximal amount of information from testing one or a few specimens. No single protocol can represent all earthquakes. Amplitudes and numbers of cycles are selected to best represent the earthquake characteristics of the selected seismic zone. A program with large number of small (inelastic) cycles can introduce different damage and failure modes than a program with a small number of large cycles. The sequence of different amplitudes can affect the result to a certain extent. The risk of introducing low cycle fatigue failure may become a concern when more than three cycles are used for each amplitude level.

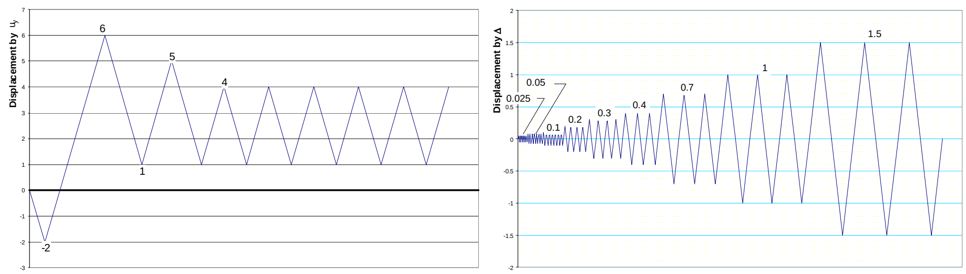
Table 4 shows the four purposes of the cyclic loading protocols. Group I consists of the currently most popular protocols. The ACI moment frames acceptance testing program (ACI [4]) shown in figure 4a and the program developed for steel moment frames in ATC-24 (ATC [2]) shown in figure 4b are deemed adequate for bridge pier testing. The displacement amplitude and number of cycles of these protocols are based on statistical studies of earthquake responses. The sequence of cycles with different amplitude is rather set for convenience and ease of observation. The gradual increasing amplitude that starts within elastic range makes the limit states to reveal one by one and allows modification to the program when problems are found.

Table 4 Programs for different purposes

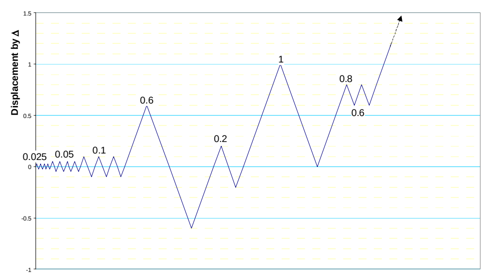
	Ordinary Earthquakes	Near-fault Earthquakes
Ductile	I	II
Non-ductile	III	IV



(a) Type I (ACI, 2001) (b) Type I (ATC, 1992)



(c) Type II (SAC Joint Venture, 1997) (d) Type III (Krawinkler et al, 2001)



(e) Type IV (Krawinkler et al, 2001)

Figure 4 Protocols for different purposes (a) Ordinary earthquake on ductile specimen (type I) (b) Alternative program for ordinary earthquake on ductile specimen (c) Near-fault earthquake on ductile specimen (type II) (d) Ordinary earthquake on non-ductile specimen (type III) (e) Near-fault earthquake on non-ductile specimen (type IV)

Group III protocol is the variation of group I for the specimen without clear definition of yielding. The expected maximum displacement (Δ) is used as the reference in the program instead of yielding displacement (u_y) used for group I.

Group I and III are developed with considerations of normal earthquakes, normal site conditions, and normal structural systems. For example, the non-ductile program uses a typical California (Los Angeles) seismicity, type D soil profile (Caltrans SDC), and structural period of 0.2 to 1 sec. Variations need to be considered for bridge pier testing targeting at a specific site and structure.

Group II and IV are the protocols for studies that target pier performance under near-fault ground motions. The near-fault protocol developed for long-period steel moment frames in SAC program (Krawinkler et al [9]) is one of the few protocols in group II. The CUREE-Caltech Woodframe Project (Krawinkler et al [5]) developed a near-fault protocol for non-ductile member testing, i.e. a group IV protocol. The near-fault protocols provide a measure of response to large amplitude impulsive load in the early stage of an earthquake.

The loading protocols are not to be blindly followed. Certain modification or extension according to testing requirements can largely increase the value of the testing results and the ease of execution. The test data after the designated performance target has been achieved can have significant value. The users of the FHWA guidance document is strongly encouraged to continue testing exceeding the specified range of the protocols, until failure.

(3) Bidirectional cyclic load

Bidirectional testing programs are specified in a coordinate system consisting of two principal axes. The definition of the principal axes varies for different purposes. If the subject component belongs to a bridge with no skew and no curve, the two axes of symmetry, associated with longitudinal and transverse directions, can be conveniently assigned as the principal axes for the biaxial loading.

Many shapes of the cycles are available in the market. There has not been a consensus on which gives more precise simulation to the two-dimensional seismic response. Figure 5 shows several existing cyclic programs. Each program produces specific level and unique style of damage. They can be combined or be reversed in polarity to provide the desired level of severity and level of symmetry.

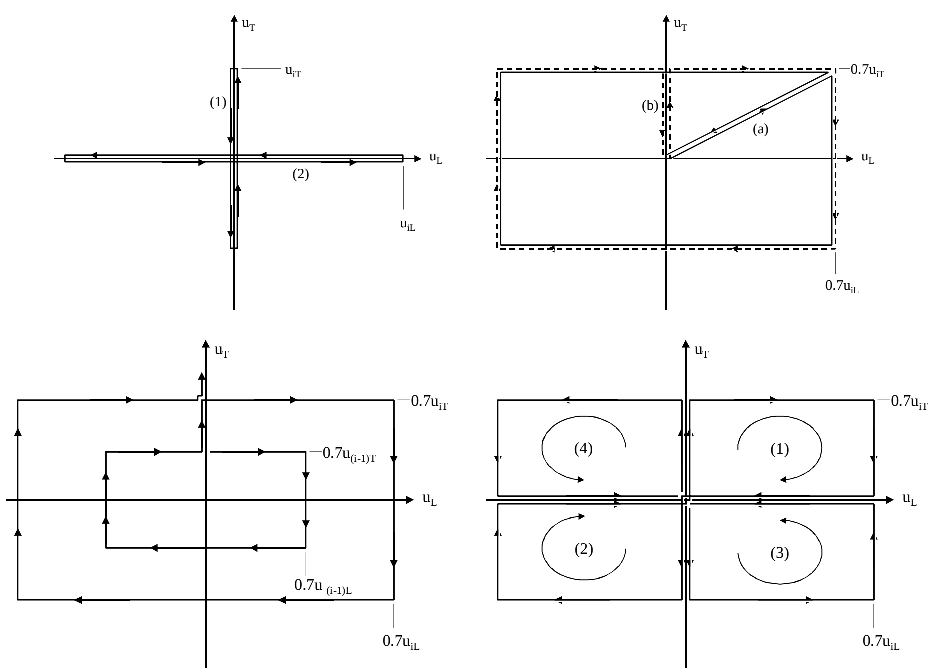


Figure 5 Existing bidirectional loading programs

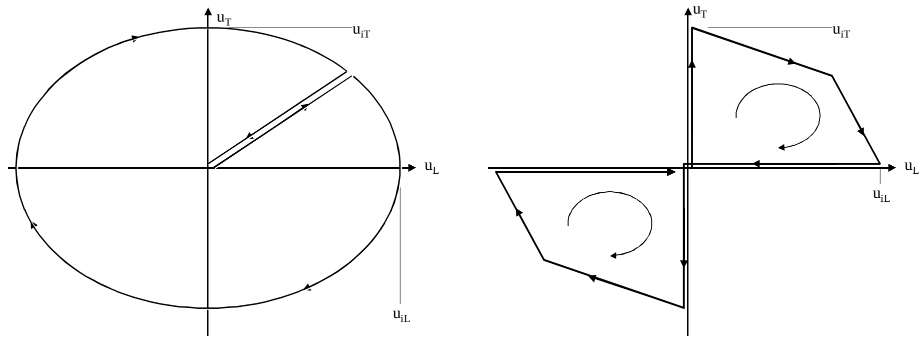


Figure 5 (cont.) Existing bidirectional loading programs

(4) Earthquake records

When earthquake records are used, the objective is to faithfully reproduce the selected earthquake event. To reproduce the original ground motion, both the control command (the digital record) and the performance of the loading apparatus must meet certain quality requirement. In the acquisition and distribution of ground motion records, intentional or unintentional modifications may occur. It is preferred in a test that the original records are obtained from a reliable source (see databases listed in table 5) and are used directly or modified only once for the test requirement. Most earthquake records in the databases are corrected and/or filtered to provide consistent representation of earthquake properties. The users need to have fundamental understanding of the data processing techniques associated with the records to determine adequacy of the record for the testing.

Table 5 direct sources of ground motion records

Institute or Agency	Contact
California Geological Survey	ftp://ftp.consrv.ca.gov/pub/dmg/csmip/
COSMOS Virtual Data Center	http://db.cosmos-eq.org/
Pacific Earthquake Engineering Research Center (PEER)	http://peer.berkeley.edu/research/motions/ http://peer.berkeley.edu/smcat/index.html
US Geological Survey	http://smftp.wr.usgs.gov/

It is not desirable to resize an earthquake to match the event size that the prototype pier is designed for. A record uniformly multiplied by a factor less than one can have very different characteristics with one that is originally smaller. Original earthquake records that satisfy the earthquake parameter requirements (PGA, response spectrum, or other control parameters) for the prototype should be selected from earthquake record databases and subsequently scaled in accordance with a proper similitude rule. A record that has been reshaped to match prototype design parameters (modified time-history or response spectrum) can only be treated as a simulated record.

The events used in an array of ground motion records should represent a reasonable series of earthquake and aftershock events. An example can be found in the work of El-Bahy et al [10].

Axial load effect

The effect of axial load under lateral deformation can be separated into two parts. One part comes from the horizontal offset of the axial loading point with respect to the fixed end of the element, which is referred to as the P-Δ effect. The other part comes from the swaying of the axial loading mechanism. The P-Δ effect is a realistic condition that occurs in bridges when excessive horizontal displacement takes place. It cannot be simulated except by an axial loading machine or a weight block that keeps the same loading direction throughout the test. The swaying of the loading mechanism generates an additional lateral force (positive or negative) that varies with the amount of swaying. Figure 6a shows possible axial loading directions and their effect. The vertical downward force (i) is the vertical component of the push-down type axial loading mechanism (ii) or pull-down type axial load mechanism (iii). The typical push-down and pull-down mechanisms are shown in figures 6b and 6c, respectively. The vertical component (i) acting at an offset (displacement u) produces the P-Δ effect. The horizontal component of the swaying axial load mechanism (ii) or (iii) becomes an addition or reduction to the lateral loading (iv). P-Δ effect is a realistic phenomenon and does not need to be considered in loading program. The only exception is when the bending moment and curvature at a specific cross-section are used as control parameters in the loading program. For such case, the moment from P-Δ effect can be combined with that from lateral load.

The P-Δ effect generates various additional bending moments at different sections in the specimen depending on the shape of deformation, in contrast with triangular bending moment profile from other lateral loads (see comparison in figure 6d). The maximum additional bending moment taking place at the base of the column is used as a benchmark for its effect on the test result. As shown in figure 6a, the additional bending moment at the base of the column is the axial force multiplied by the displacement.

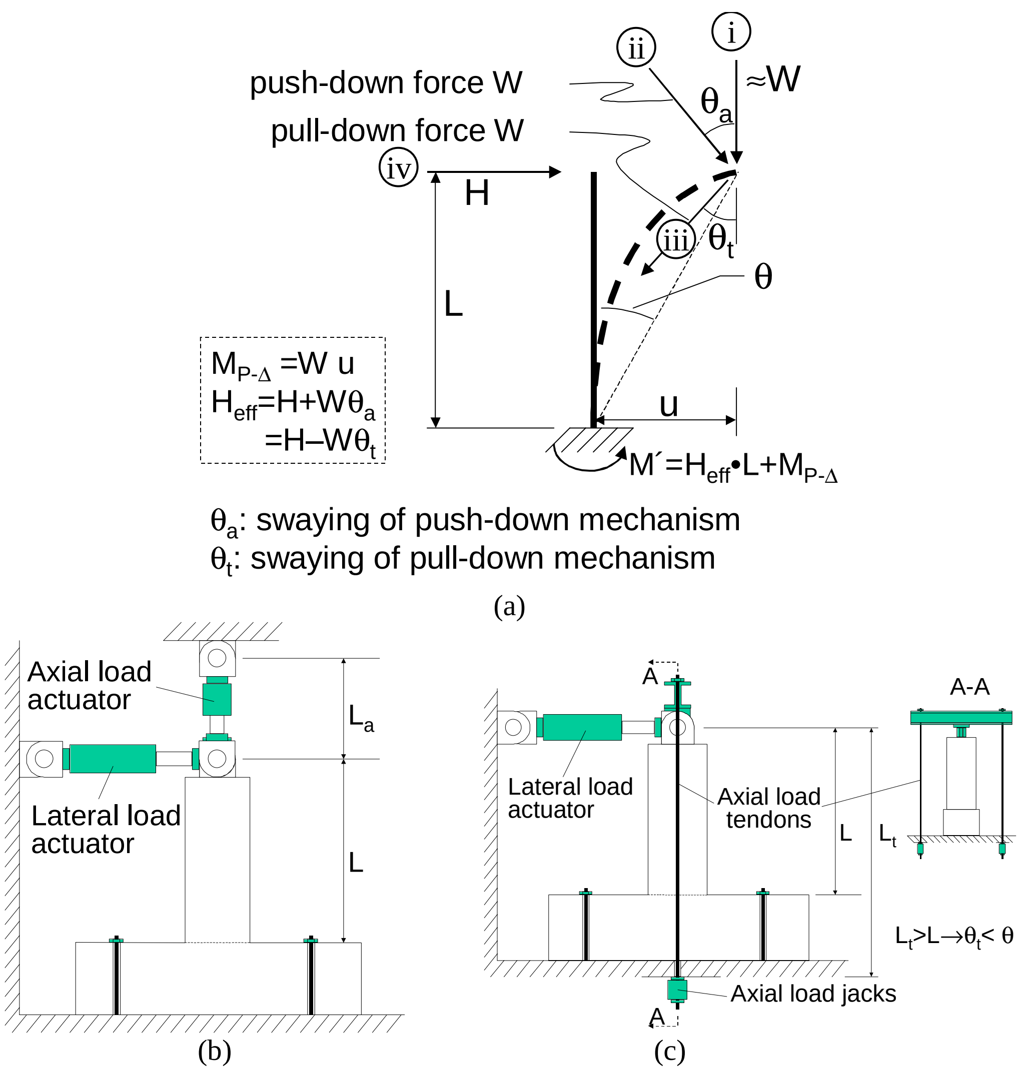
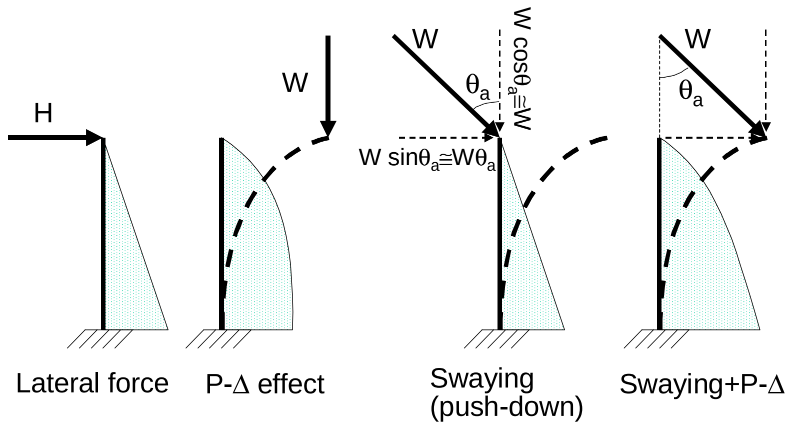


Figure 6 Axial load effect (a) Effective lateral load and P-Δ effect (b) Typical push-down mechanism (c) Typical pull-down mechanism



(d)

Figure 6 Axial load effect (cont.) (d) Bending moment profiles for lateral load, P-Δ effect, and swaying effect

Measurement and documentation

Thorough and accurate measurement and documentation are necessary components for a successful experimental testing project. The quantity and quality of measurement in the seismic performance testing are both important. It was found in this study that a large amount of testing data are discarded right after the originally designated purpose was served. A seismic performance test of the bridge pier normally bears much more information than that is needed by the person(s) who conduct the experimental work. Both theoretical and experimental researchers benefit from the multiple data sources that consist of verifiable testing conditions. The effort spent on establishing experimental databases in the latest years (Hose et al [8]) indicated the increasing demand on data archiving and sharing. Earlier data in these databases contain very basic measurements, such as only force to drift-rotation relationship. It is difficult to conduct in-depth studies based on these data. The future performance databases and the extension of the existing databases will likely contain much more information. It is an ethical obligation for the persons who conduction experimental works to provide sufficient data to be archived.

The quality of measurement depends on the quality of the equipments and installation/operation. The experimentalists need to carefully select and operated the equipment, as well as include detailed description in the testing report. The calibration of the measurement system is crucial to the quality of data. Since nearly none of the seismic performance testing of bridge piers is for quality control, NIST-traceable calibrations are not required. Reasonably reliable calibration procedures are acceptable.

Figure 7(a) shows an example of minimum requirement for the external measurement for most slow testing. Figure 7(b) is an example for shaking table testing. These measurements are essential to describing the state of stress, deformation, the damage of the specimen. The person who conducts the experimental work may not need all the measurement. Nonetheless, such a small investment can make the testing results much easier to be used in other research or to be included in the performance database.

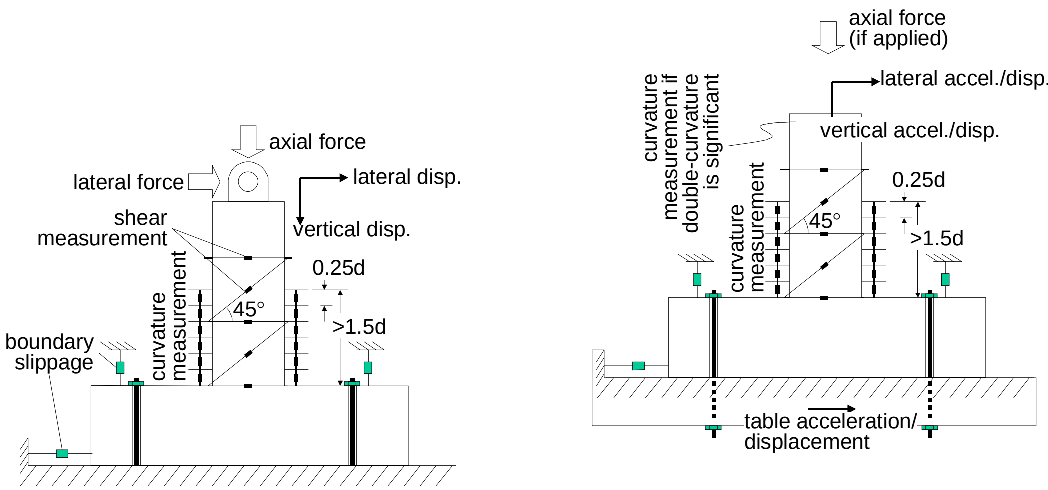


Figure 7 Required measurements (a) Quasi-static testing (b) shaking table testing

SUMMERY REMARKS

Bridge testing technology has been developing rapidly in recent years and will continue the fast growth in the near future. The FHWA guidance document can only cover the existing technology and cannot be treated as an exclusive guideline for all seismic performance testing of bridge piers. Revisions will be made along time to include emerging technology.

Elaborate planning and detailed documentation in every step of testing is encouraged. The sustainability of the testing data can be promoted by setting up the minimum measurement/documentation requirement. The data utilization is further enhanced by planning for multiple testing objectives (for example, testing both for theoretical research and proof-of-concept).

The FHWA guidance document provides assistance to the bridge seismic research and engineering practice with the following functions:

(1) It provides minimum requirements on testing condition and loading protocols to make comparisons between testing data from different experimental studies easier.
(2) It provides minimum requirements on instrumentation and documentation to promote multiple usage of testing data.
(3) It describes current practice of bridge pier testing and requirements on testing data. The developers of integrated experimental networks and performance databases can use this document as a reference to keep bridge testing in their scope.

At the time of submission of this manuscript (March 2004), the FHWA guidance document for seismic performance testing of bridge piers is at its final stage of technical revision and will be published in a short time.

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